New Applications in Food Irradiation

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INTRODUCTION

This article deals with the application of ionizing radiation (IR) to foods so as to improve their safety, shelf-life, and quality. The topics covered include: the types of equipment used to generate IR, and their advantages and disadvantages; IR's mode of action in foods; the latest information on the safety and nutritional quality of irradiated foods; current topics of research for irradiated meats and produce; a discussion of the economics of irradiated food, including case study analysis; and a summary of the current regulations governing what foods and packaging materials can be irradiated and what doses they can be given. The goal of this article is to provide the most up-to-date, scientifically accurate information on what food irradiation is and how it is being applied now, and likely applications in the near future.

GENERAL PRINCIPLES OF FOOD IRRADIATION

Food irradiation is the process of using IR to improve the safety and shelf life of meats, poultry, fruits and vegetables, eggs, spices, and other foods. Through decades of research, food irradiation has been consistently judged to be a safe, effective processing technology, resulting in wholesome and nutritious foods.[1,2] Unlike more familiar forms of radiation such as light, radio waves, or microwaves, IR is sufficiently powerful to break apart or ionize molecules and atoms. Within living cells, IR can directly break DNA, and, more significantly, split water molecules into molecular oxygen and hydrogen, as well as hydrogen and hydroxyl radicals. These powerfully disruptive chemical species damage DNA, RNA, proteins, and cellular structures, resulting in cell injury and death.[2,3] IR can be natural [X-rays, gamma rays, and high-energy ultraviolet (UV) radiation] or artificially generated (accelerated electrons and induced secondary radiation). In the context of food irradiation, IR is one of three types: an accelerated beam of electrons ("E-beam"), X-rays (obtained by impinging an E-beam on a metal target), or gamma rays (emitted as a decay product of cobalt-60 or cesium-137). Each form of IR has significant advantages and disadvantages for the treatment of foods (Table 1).

REGULATORY LIMITS

The dose delivered to foods is measured in kiloGrays (1 kGy = 0.1 Mrad). Legislative bodies around the world have set regulatory limits on the foods that are permitted to be irradiated, the purpose of irradiation, and doses to be applied. Depending on the regulator, these limits may be expressed as a minimum dose, maximum dose, or an approved dose range. The US government has approved a variety of foods for irradiation (Table 2). Proposals are pending with the US Food and Drug Administration (FDA) as of 2005 to allow additional specific commodities and broad commodity classes to be irradiated.

WHOLESOMENESS OF IRRADIATED FOODS

Toxicological Safety

Over the decades since IR was first proposed as a food-processing tool, irradiated foods have been the subject of numerous short-term, medium-term, and long-term (multigenerational) animal feeding studies and chemical and biochemical analyses of irradiated foods and food components. Following a comprehensive review of the voluminous body of research on the safety of foods irradiated up to 10 kGy, the World Health Organization determined[4] that foods so treated posed no exceptional risk to consumers. This exceptionally high dose represents a level of treatment that would cause significant sensory damage to most foods; from a practical standpoint, the maximum dose that will be used for any given commodity will be well below this threshold.

As chemical analysis methods improve, the debate on the toxicological safety of irradiated foods continues. The IR induces changes in the chemistry of

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Table 1 Food irradiation technologies

Factors	Electron beam	X-ray	Gamma
Source	Accelerated electrons, typically 5–10 MeV[a]	Induced by impingement of electron beam onto a metal plate. Conversion efficiency is 5–10%	Radioactive decay of Co-60 (2.5 MeV) or Cs-137 (0.51 MeV)
Operator shielding required	During operation[b], >2 m concrete or 0.7 m steel/iron/lead	During operation[b], >2 m concrete or ~0.7 m steel/iron/lead	>5 m water or >2 m concrete or 0.7 m steel/iron/lead
Processing time[c]	Seconds	Seconds	Minutes (depending on source strength)
Penetration[d]	6–8 cm, suitable for relatively thin or low density products	30–40 cm, suitable for all products	30–40 cm, suitable for all products
Special considerations	Maintenance of high-voltage electronics	Maintenance of high-voltage electronics. Metal fatigue and degradation of target plate owing to heating	Reduction of source strength over half-life[e] of Co-60 (5.27 yr) or Cs-137 (30.17 yr). Periodic source replenishment required

[a]MeV = million electron volts.
[b]When electron beam is not powered, no radiation is emitted.
[c]Processing time required to deliver dose appropriate for commodity and intended purpose.
[d]Idealized penetration in a homogeneous food matrix of 1 g/cm^3. Influenced by edge effects and heterogeneous variations in density (voids, bone, fibrous matter, etc.).
[e]Radioactive half-life is the time required for the strength of a radiation source to diminish by 50%. After 10.5 yr, a Co-60 source would have 25% of its initial strength, while a Cs-137 source would have approximately 80% of its initial strength.

treated foods, resulting in the formation of chemical by-products, some of which are known toxins. The vast majority of these radiolytic products are also found in unprocessed foods and in foods treated with conventional processing techniques,[2] and thus are not unique to irradiated foods. Unique radiolytic products, i.e., chemicals by-products that are only formed in foods by IR, have been a topic of recurrent attention. Recently, questions have focused on the potential toxicity of a class of compounds known as 2-alkylcyclobutanones, which are generated at low levels in meats and poultry by IR.[2,5] The genotoxicity of the most common of these, 2-dodecylcyclobutanone (2-DCB), has been the subject of particular attention. In one study, even when tested at exceptionally high levels, 2-DCB was not associated with damage to cellular DNA.[5] Smith and Pillai[2] recently summarized a series of studies examining the evidence related to this class of compounds, and 2-DCB in particular. The overall body of evidence indicates that 2-DCB, in particular, and irradiated foods, in general, pose no meaningful toxicological risk.

Table 2 US code of federal regulations 21CFR179.26: applications and dose limits for irradiated foods

Commodity and purpose	Dose limits
Control of *Trichinella* in pork	0.3–1.0 kGy
Suppression of growth and maturation in fresh foods	Maximum dose 1.0 kGy
Disinfestation of insect pests	Max. 1.0 kGy
Antimicrobial treatment of dry enzymes	Max. 10.0 kGy
Antimicrobial treatment of dry herbs and spices	Max. 30.0 kGy
Control of pathogens in fresh and frozen raw poultry	Max. 3.0 kGy
Sterilization of foods intended for use by NASA	Minimum dose 44.0 kGy
Control of pathogens and extension of shelf life of refrigerated and frozen meats	Max. 4.5 kGy (refrigerated), Max. 7.0 kGy (frozen)
Control of *Salmonella* in fresh shell eggs	Max. 3.0 kGy
Control of pathogens in seeds used to produce sprouts	Max. 8.0 kGy

Nutritional Value

The nutritive value of macronutrients such as lipids, carbohydrates, and proteins is unaffected by IR, even at high doses.[1,2] The potential for loss of micronutrients in irradiated foods has been studied extensively. Minerals and most vitamins are generally unaffected by IR. At high doses, IR can cause the loss of some micronutrients, most notably vitamins A, B1, C, and E. One commonly held misunderstanding is in regard to loss of vitamin C (ascorbic acid) in irradiated foods. It is known that IR causes the oxidation of ascorbic acid to dehydroascorbic acid. However, because dehydroascorbic acid is readily reduced back to ascorbic acid, the IR-induced oxidation does not truly represent a loss of the functional value of the vitamin.[1] Based on a review of the science, the US FDA has concluded that IR has effects on food nutritive value which are similar to those of conventional food processing techniques.[2]

MEAT AND POULTRY

Irradiated animal products such as beef, pork, lamb, chicken, and turkey have been the subject of extensive research.[2] The amount of IR required to effect a substantial reduction (greater than $3 \log_{10}$ units, or 99.9%) of contaminating pathogens has been shown to result in minimal change of sensory quality to these meats. The antimicrobial efficacy of IR is influenced by the type of meat tested and the chemical additives and preservatives often used in meat and poultry processing. A relatively new area of research is the use of IR to reduce pathogens in complex ready-to-eat (RTE) foods such as deli meats and assembled meals such as sandwiches. These products represent a new challenge from a food safety standpoint, as they are typically eaten with little or no preparation by the consumer, and must therefore have a low in-package risk profile. The composition of the meal and the physical location of the contaminating bacteria within the food influence the efficacy of IR.[6] IR is typically applied as a final processing step, postpackaging, and thus is ideally suited for application to this type of food product. New regulations to approve IR for use with complex RTE foods are currently under review.

FRUITS AND VEGETABLES

Disinfestation

The use of fumigants such as methyl bromide has been discontinued in U.S.A. and Europe, creating a need for an effective alternative. Cold shock and heat treatments have a limited applicability, owing to their effects on produce quality.[1] IR is seen as especially promising in this context, and is expected to become more important in the coming years. Extermination of arthropod pests in fresh fruits and vegetables requires a radiation dose lethal to the target insect, up to 3 kGy. However, sterilization of the insects, thereby preventing reproduction during or after storage, can be achieved by lower doses, typically 0.03–0.2 kGy—levels that most types of produce can easily tolerate.[1]

Pathogen Reduction

Food-borne illness outbreaks in the U.S.A. associated with contaminated fruits, vegetables, salads and juices have risen from less than 20 throughout the 1970s to more than 100 in the 1990s.[7] A variety of new technologies have been proposed to improve the safety of fresh and fresh-cut produce; low-dose IR is one of the more promising of these. Of particular interest is the potential for combination of IR with modified atmosphere packaging,[8] chemical rinses,[9] or other interventions to achieve safer produce.[1] The key, with application of IR to fresh and fresh-cut produce, is reducing the pathogen risk while maintaining the quality of these relatively fragile commodities.

COMMERCIAL FACTORS

Economics

A recurrent issue regarding irradiated food is the cost relative to conventional nonirradiated foods. The extra processing step will necessarily incur additional costs in production. Assuming that treatment of product is arranged as a contract service with an independent irradiation facility, rather than by means of irradiation equipment incorporated into an existing food processing plant, cost estimates are dependent on factors such as the throughput capacity of the irradiation plant, storage/shipment/transshipment costs, etc. As recently summarized,[1] the ancillary market benefits (reduction of storage losses, premium prices commanded by specialty markets, etc.), may be offset by ancillary market drawbacks (necessity for increased public education/outreach spending, potential for increased regulatory oversight, etc.).

The various factors that determine the additional costs for IR processing complicate theoretical calculations of price premiums and return on investment for any given irradiated commodity. One real-world

Table 3 US code of federal regulations 21CFR179.45: packaging materials approved for irradiated foods

Material	Maximum dose
Nitrocellulose-coated or vinylidene chloride copolymer-coated cellophane	10 kGy
Glassine paper	10 kGy
Wax-coated paperboard	10 kGy
Films of polyolefin or polyethylene terephthalate. These may contain:	10 kGy
Sodium citrate, sodium lauryl sulfate, polyvinyl chloride[a] Coatings comprising a vinylidene chloride copolymer containing a minimum of 85% vinylidene chloride with one or more of the following comonomers: Acrylic acid, acrylonitrile, itaconic acid, methyl acrylate, and methyl methacrylate	
Kraft paper (only as a container for flour)	0.5 kGy
Polystyrene film	10 kGy
Rubber hydrochloride film	10 kGy
Vinylidene chloride–vinyl chloride copolymer film	10 kGy
Nylon 11	10 kGy
Ethylene–vinyl acetate copolymers	30 kGy
Vegetable parchments	60 kGy
Polyethylene film[a]	60 kGy
Polyethylene terephthalate film[a]	60 kGy
Nylon 6 films[a]	60 kGy
Vinyl chloride–vinyl acetate copolymer film[a]	60 kGy
Acrylonitrile copolymers[a]	60 kGy

[a]This material may be amended with additional materials, listed in Table 4.

example that serves as a useful case study is the US Department of Agriculture's National School Lunch Program (NSLP). In 2004, the NSLP introduced irradiated ground beef as a voluntary option for participating schools. The pricing and purchasing specifications for this program indicate that irradiated ground beef will cost approximately \$0.14–0.20/lb more than comparable nonirradiated product.[10]

Packaging

The packaging used for foods to be irradiated must withstand the processing without suffering loss of mechanical properties such as gas permeability, shear strength, UV blockage, etc. The material must also be resistant to IR-induced degradation, and potential migration of degradation by-products into the foods within the package. The US government has specified a list of packaging materials approved for irradiation, along with a maximum radiation dose specified for each (Table 3). Some of these materials may be amended, up to a specified amount, with adjuvants such as preservatives, waxes, oils, etc. (Table 4).

Consumer Acceptance

Despite the promise of IR, consumer acceptance of the technology continues to lag. This is, in part, because of negative connotations associated with the term "irradiation," and also owing to consumer

Table 4 US code of federal regulations 21CFR179.45: adjuvants and amendments approved for incorporation into certain packaging materials approved for irradiated foods

Adjuvant/amendment	Limit (by wt. of polymer)
Amides of erucic, linoleic, oleic, palmitic, and stearic acid	1%
BHA (butylated hydroxyanisole)	1%
BHT (butylated hydroxytoluene)	1%
Calcium and sodium propionates	1%
Petroleum wax	1%
Mineral oil	1%
Stearates of aluminum, calcium, magnesium, potassium, and sodium	1%
Triethylene glycol	1%
Polypropylene, noncrystalline	2%

advocacy groups opposed to the technology's connection to radioactive materials. Educational campaigns by public health bodies are known to be an effective means to address the former, while the increasing reliance on e-beam and X-ray, rather than isotope sources, has served to respond to the latter. As the public becomes more familiar with food irradiation, consumer acceptance will similarly expand.

CONCLUSIONS

As food processing becomes increasingly centralized, the risks presented by food-borne pathogens are shared by ever-widening populations. IR is an effective tool that can improve the safety and quality of meats, poultry, and produce when used properly. It is a process that is uniquely able to reduce the risk of bacterial contaminants, improve shelf life and maintain quality, and do so in an economical and commercially feasible way. However, it is also a technology that is underutilized in the current market. In the coming decade, education and outreach will help consumers to understand the advantages of this process, and market penetration will increase. New research on the combination of irradiation with other antimicrobial interventions will allow the application of this technology to juices, complex RTE foods, fresh and fresh-cut produce, and other foods, ultimately for the benefit of consumers.

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